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Duplessis et al.

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(54) **INTEGRATED TRANSFORMER**

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H01F 27/28 (2006.01)

(52) **U.S. Cl.**

CPC **H01F 27/2895** (2013.01)

(58) **Field of Classification Search**

USPC 336/65, 200, 232; 257/531

See application file for complete search history.

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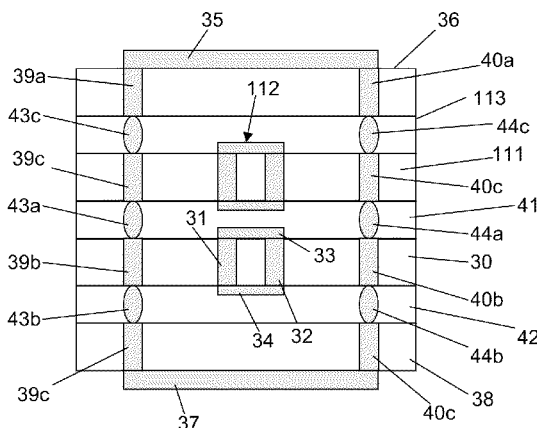
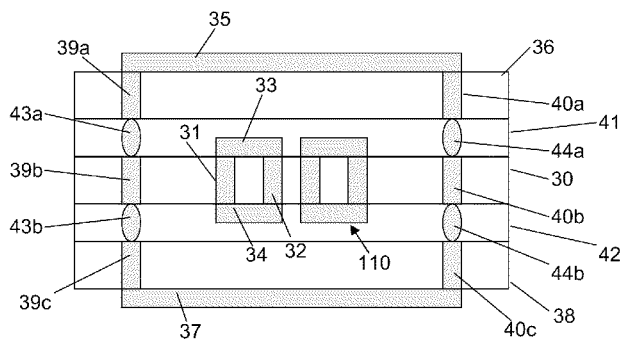
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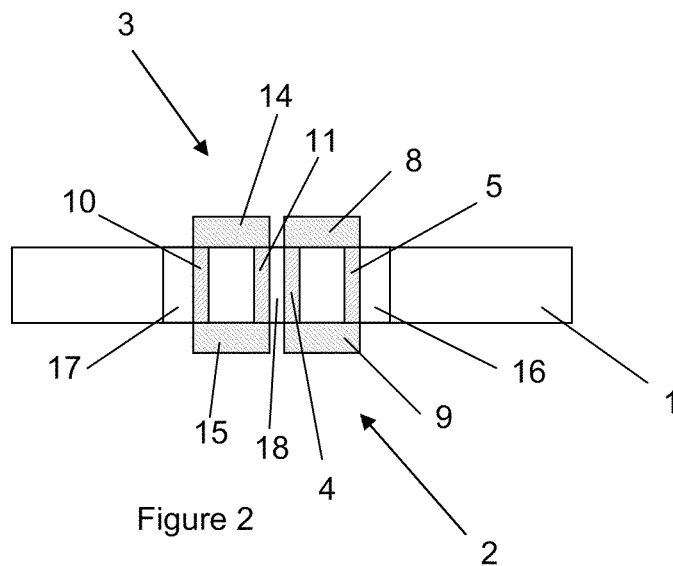
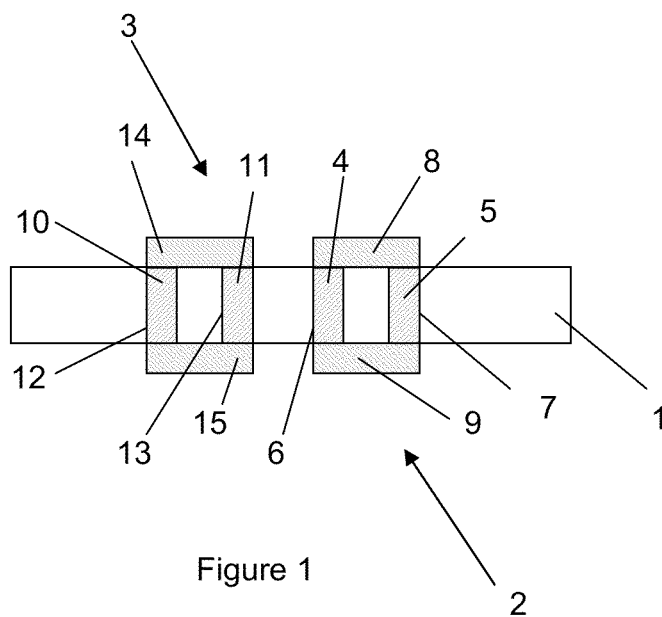
Primary Examiner — Tuyen Nguyen

(57) **ABSTRACT**

A transformer comprising primary and secondary windings is disclosed. Each winding has first and second metal capping layers coupled together electrically in parallel by a metal connector passing through a substrate lying between the first and second metal capping layers.

7 Claims, 11 Drawing Sheets





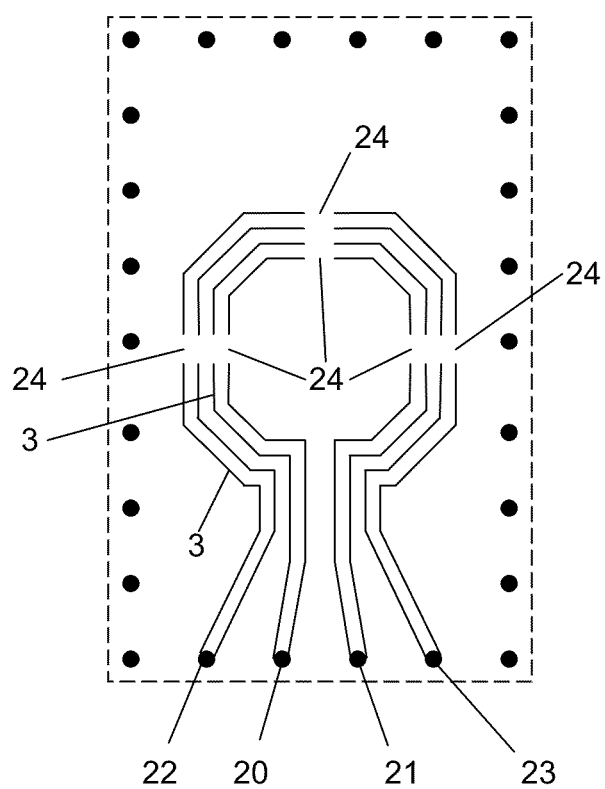


Figure 3

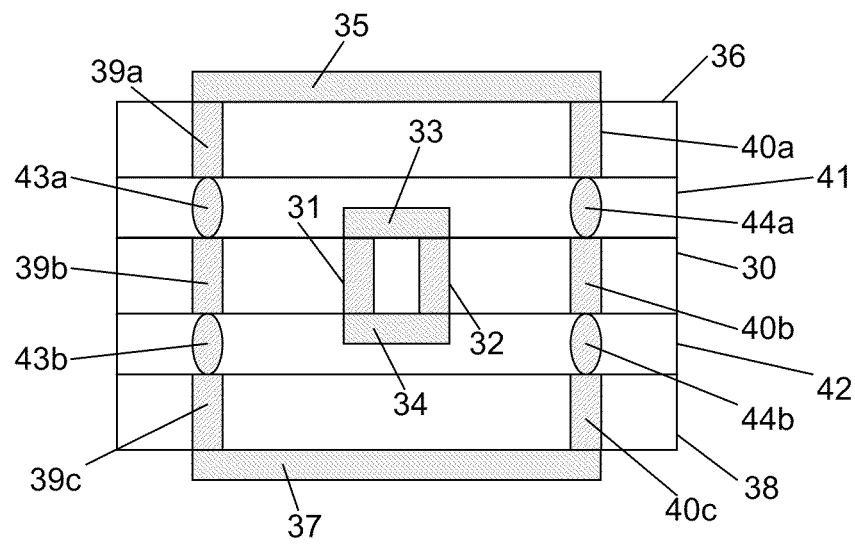
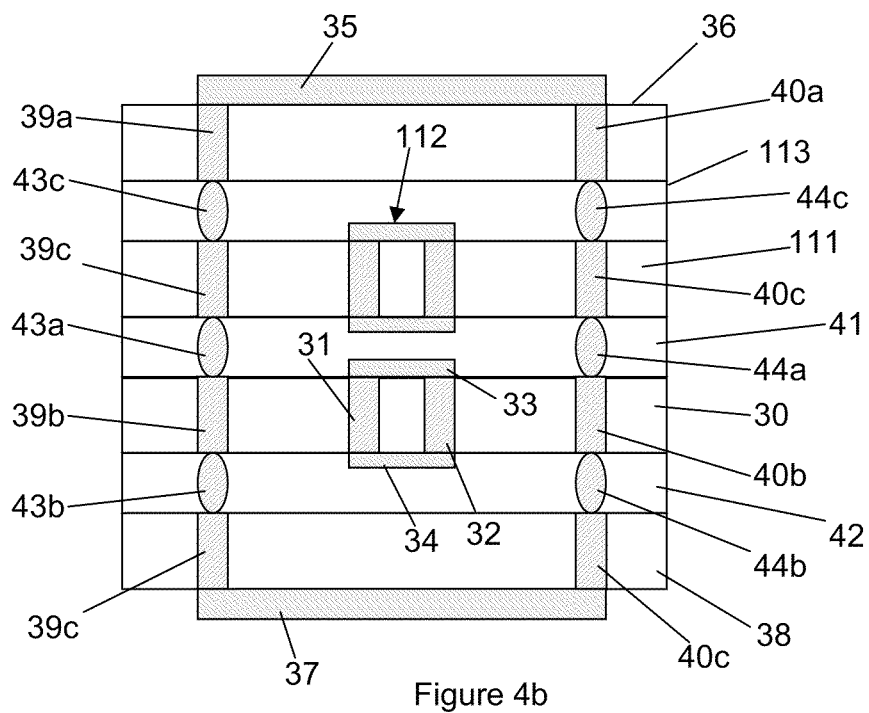
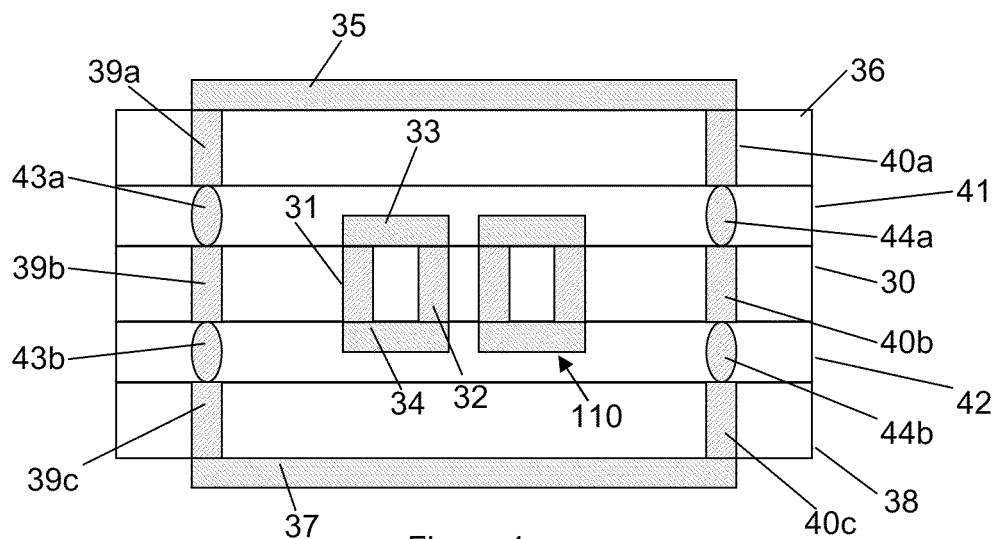


Figure 4



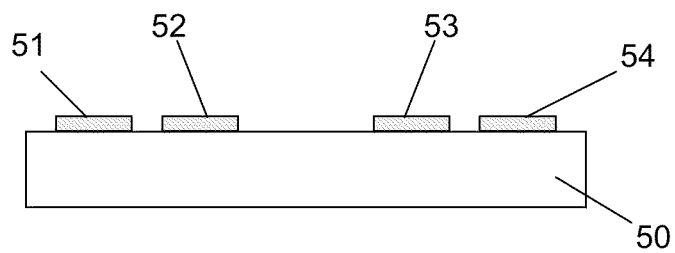


Figure 5a

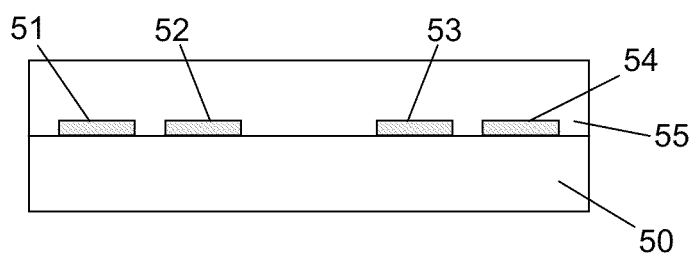


Figure 5b

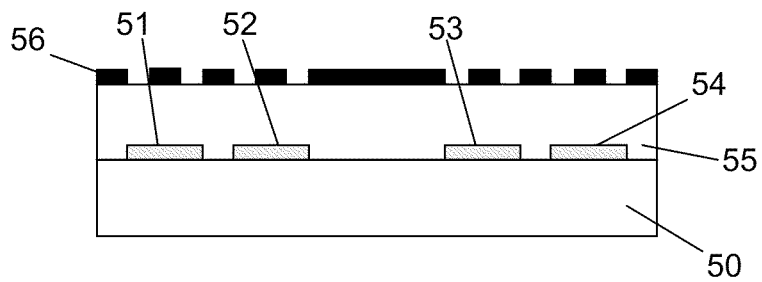


Figure 5c

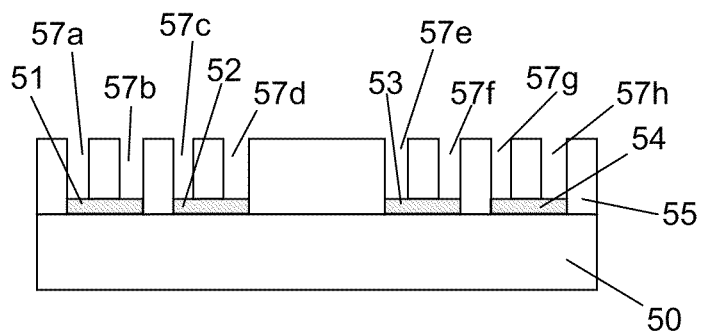


Figure 5d

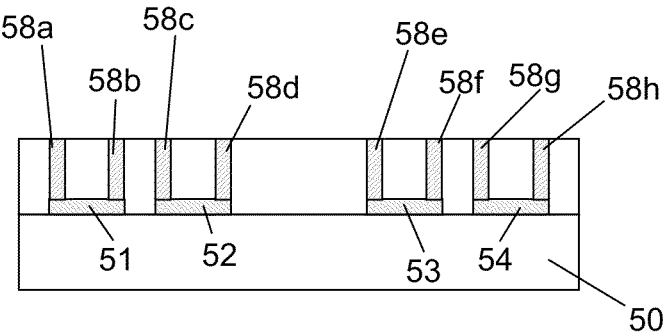


Figure 5e

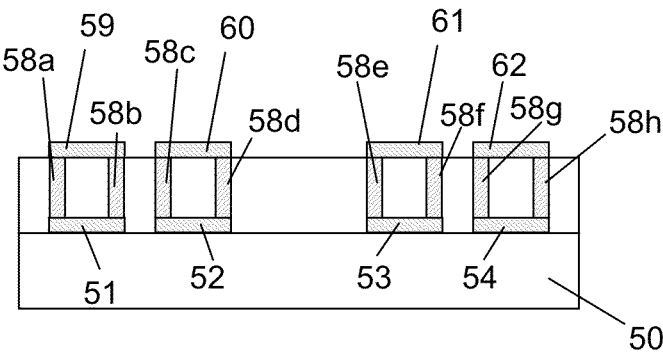


Figure 5f



Figure 6a

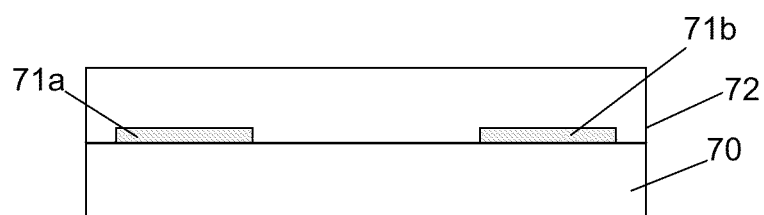


Figure 6b

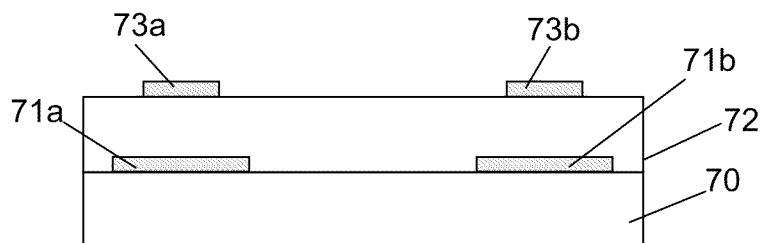


Figure 6c

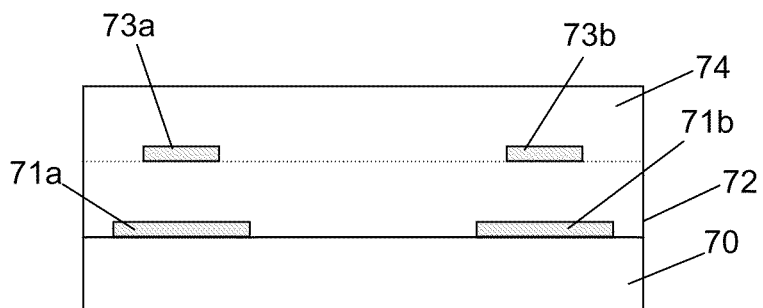


Figure 6d

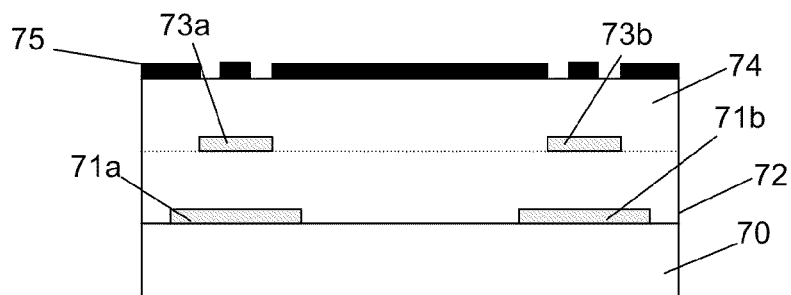


Figure 6e

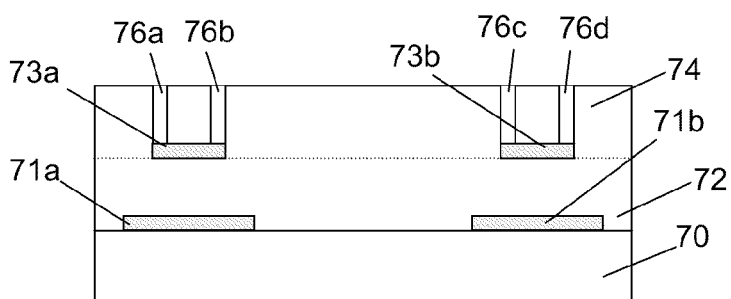


Figure 6f

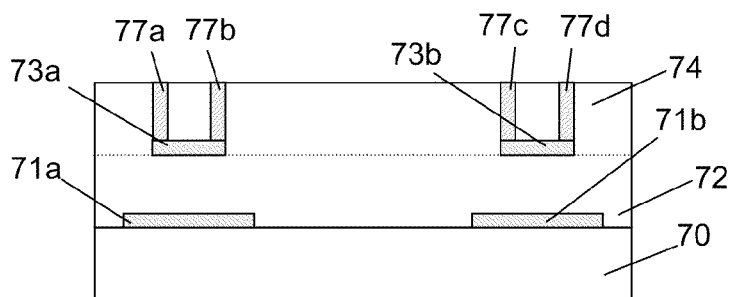


Figure 6g

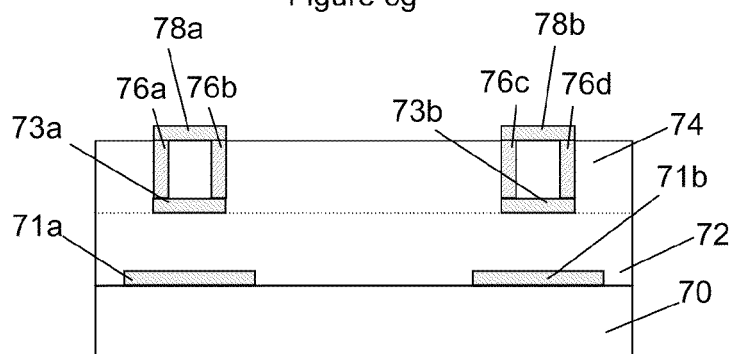


Figure 6h

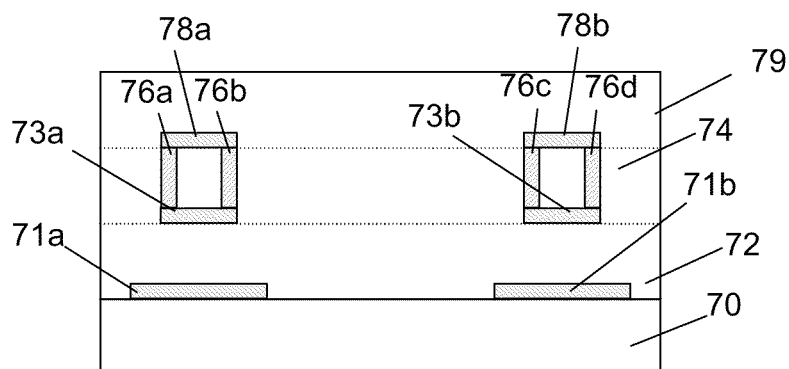


Figure 6i

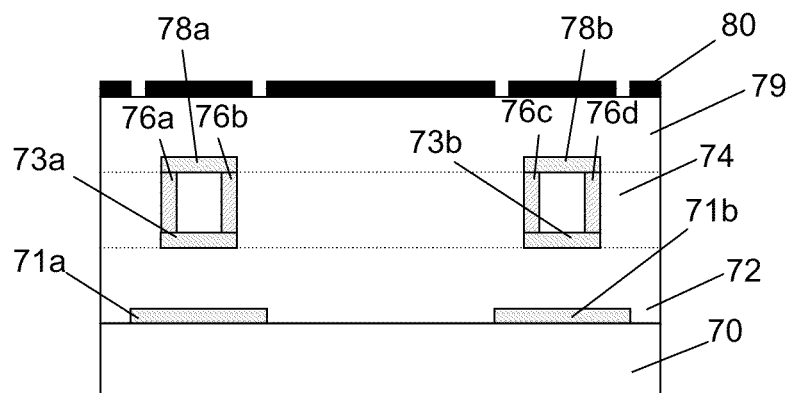


Figure 6j

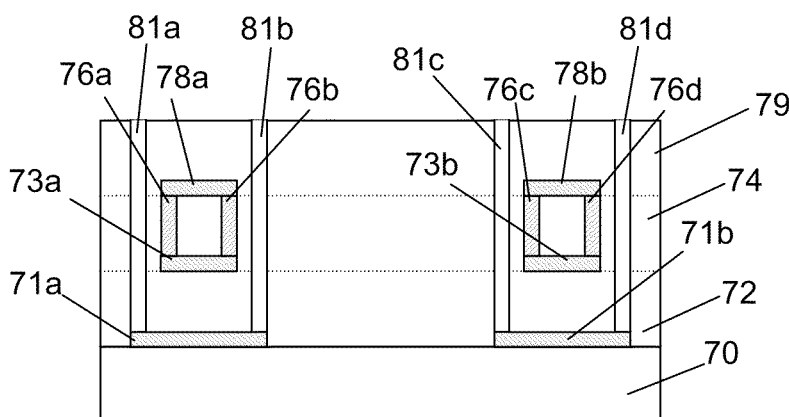


Figure 6k

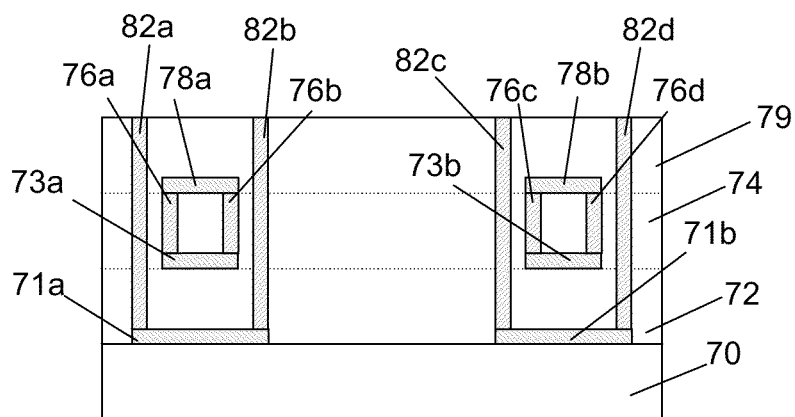


Figure 6l

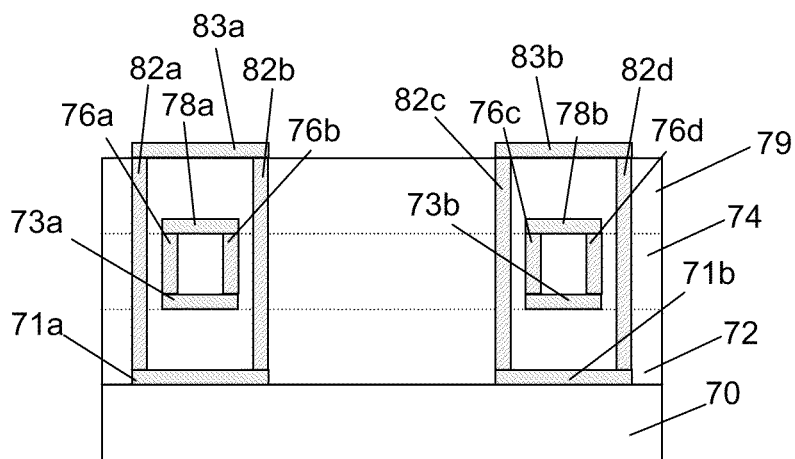


Figure 6m

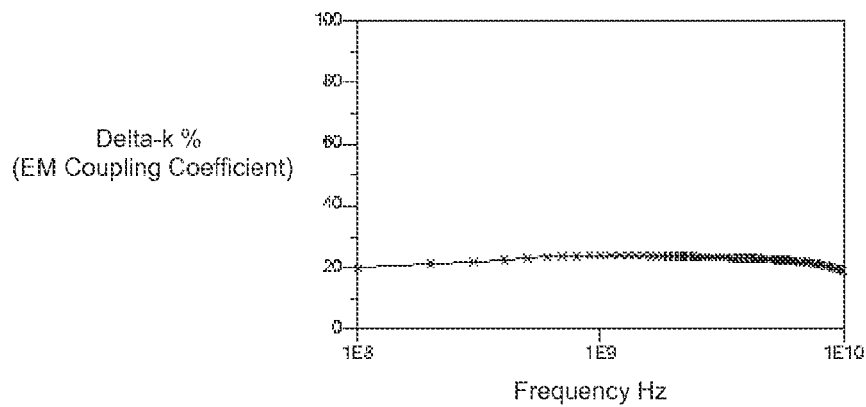


Figure 7a

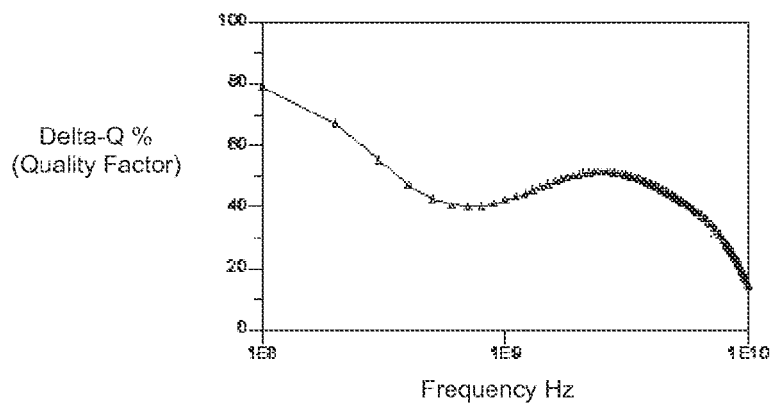


Figure 7b

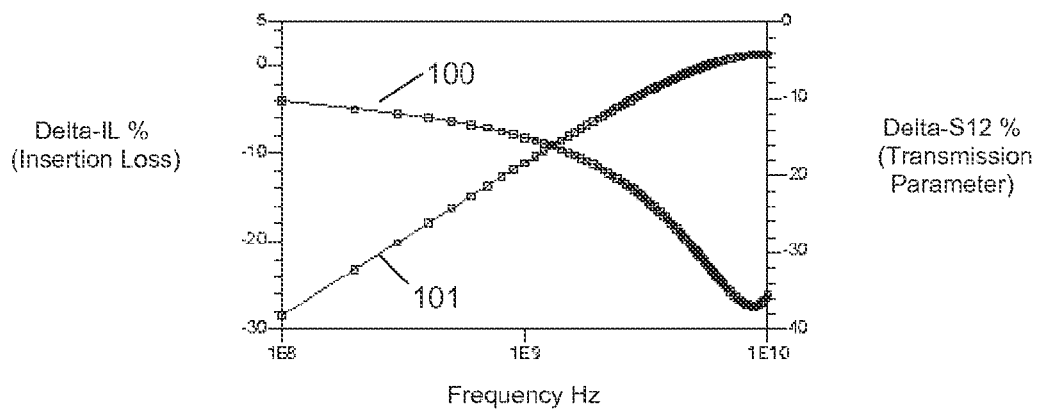


Figure 7c

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INTEGRATED TRANSFORMER

This application claims the priority under 35 U.S.C. §119 of European patent application no. 10290243.4, filed on May 5, 2010, the contents of which are incorporated by reference herein.

The invention relates to an integrated transformer and to a method for manufacturing such a transformer.

BACKGROUND OF THE INVENTION

The main electrical parameters of a transformer that are of interest to a circuit designer are the transformer turns ratio, n , and the coefficient of magnetic coupling, k . If the magnetic coupling between windings is perfect (i.e. there is no leakage of the magnetic flux) then k is unity. On the other hand, k is zero for totally uncoupled windings. A practical transformer will have a value of k between these two extremes. Typically, for an on-chip monolithic transformer a value of k between 0.75 and 0.9 can be achieved. A higher value of k results in lower losses.

Many topologies have been proposed for on-chip transformers. However, each has its drawbacks. For example, one topology (known as a Shibata or parallel architecture) is easy to design but the total lengths of the primary and secondary windings are not equal. Hence the transformer turns ratio, n , can differ from 1 even if the same number of turns of metal are provided in each winding.

In another topology (known as the Finlay or stacked architecture) a transformer occupying a low area and hence high coupling coefficient, k , can be realised. However, special care must be taken during implementation as the design makes use of both upper and intermediate metal layers. The intermediate metal layers are generally quite thin, leading to higher electrical resistance and thus a high insertion loss. Also, the upper metal layer generally having a lower resistance than the intermediate metal layers creates an asymmetry in the electrical response of the transformer.

Another problem is brought about by the upper winding being electrically shielded from the "conductive" substrate by the lower winding, and hence the parasitic capacitance to the substrate (and the associated dissipation) differs for each winding.

In addition, there is a large parallel plate component to the capacitance between windings due to the overlapping of metal layers, which limits the frequency response.

SUMMARY OF THE INVENTION

In accordance with a first aspect of the invention, there is provided a transformer comprising primary and secondary windings, each winding having first and second metal capping layers coupled together electrically in parallel by a metal connector passing through a substrate lying between the first and second metal capping layers.

Hence, the invention provides a transformer that can be integrated on a substrate, such as a silicon substrate, and in which the windings pass through the substrate. The two windings therefore have a large cross-sectional area, reducing their resistance, and present a large electromagnetic coupling area to each other via the metal connectors passing through the substrate. As a result, the coupling coefficient is very high and the insertion loss low. The transformer is also easy to design, not suffering from the problems inherent with the stacked architecture.

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In one embodiment, the substrate is a silicon substrate and each of the first and second metal capping layers lies on top and bottom surfaces of the silicon substrate respectively.

In another embodiment, the substrate is an oxide layer and each of the first and second metal capping layers lies on top and bottom surfaces of the oxide layer respectively.

Thus, in both of these embodiments the first metal capping layer of each winding lies on the top surface of the substrate and the second metal capping layer of each winding lies on the bottom surface of the substrate.

Normally, for each winding, the substrate comprises first and second trenches, and the metal connector comprises first and second parts passing through the first and second trenches respectively, each of the first and second parts coupling the first and second metal capping layers together electrically in parallel.

Alternatively, for each winding, the substrate comprises a first trench, a first part of the metal connector passing through the first trench, the substrate further comprising a common trench through which second parts of the metal connectors for each winding pass electrically isolated from each other, each of the first and second parts coupling the first and second metal capping layers together electrically in parallel.

In one embodiment, the substrate is a first silicon substrate lying between second and third silicon substrates, each of the first and second metal capping layers for the primary winding lying on top and bottom surfaces of the first silicon substrate respectively and each of the first and second metal capping layers for the secondary winding lying on top and bottom surface of the second and third silicon substrates respectively, the metal connector for the primary winding passing through the first silicon substrate and the metal connector for the secondary winding having first and second parts passing in parallel through the first, second and third silicon substrates such that the secondary winding surrounds the primary winding.

Typically, the metal connector for the primary winding has first and second parts passing through first and second trenches in the first substrate respectively, each of the first and second parts coupling the first and second metal capping layers of the primary winding together electrically in parallel.

The first and second parts of the metal connector for the secondary winding normally pass through respective aligned trenches in each of the first, second and third substrates, each of the first and second parts thereby coupling the first and second metal capping layers of the secondary winding together electrically in parallel.

In this embodiment, a second primary winding may also be provided. In this case, first and second metal capping layers for the second primary winding may each lie on top and bottom surfaces of the first silicon substrate respectively, and the metal connector for the second primary winding may pass through the first silicon substrate. Thus, the primary winding and second primary winding lie adjacent each other on the first silicon substrate.

Alternatively, the first and second metal capping layers for the second primary winding may each lie on top and bottom surfaces of a fourth silicon substrate lying between the first silicon substrate and either of the second or third silicon substrates, and the metal connector for the second primary winding may pass through the fourth silicon substrate. In this case, the metal connector for the secondary winding passes through the fourth substrate. Thus, the primary and second primary windings lie one above the other within the secondary winding.

Multiple primary windings may be provided in this way, and the two alternatives of the above two paragraphs may be combined to provide both horizontal and vertical stacking of primary windings.

This embodiment provides a transformer where the secondary winding totally surrounds the primary winding, ensuring excellent electromagnetic coupling between the two.

The surrounding of the primary winding by the secondary winding is also achieved in another embodiment, wherein the substrate is an first oxide layer lying between second and third oxide layers, each of the first and second metal capping layers for the primary winding lying on top and bottom surfaces of the first oxide layer respectively and each of the first and second metal capping layers for the secondary winding lying on top and bottom surface of the second and third oxide layers respectively, the metal connector for the primary winding passing through the first oxide layer and the metal connector for the secondary winding having first and second parts passing in parallel through the first, second and third oxide layers such that the secondary winding surrounds the primary winding.

After manufacturing, the first, second and third oxide layers are not necessarily distinct from each other, but may be one overall oxide layer.

Typically, the metal connector for the primary winding has first and second parts passing through first and second trenches in the first oxide layer respectively, each of the first and second parts coupling the first and second metal capping layers of the primary winding together electrically in parallel.

The first and second parts of the metal connector for the secondary winding normally pass through respective aligned trenches in each of the first, second and third oxide layers, each of the first and second parts thereby coupling the first and second metal capping layers of the secondary winding together electrically in parallel.

In this embodiment, a second primary winding may also be provided. In this case, first and second metal capping layers for the second primary winding may each lie on top and bottom surfaces of the first oxide layer respectively, and the metal connector for the second primary winding may pass through the first oxide layer. Thus, the primary winding and second primary winding lie adjacent each other on the first oxide layer.

Alternatively, the first and second metal capping layers for the second primary winding may each lie on top and bottom surfaces of a fourth oxide layer lying between the first oxide layer and either of the second or third oxide layers, and the metal connector for the second primary winding may pass through the fourth oxide layer. In this case, the metal connector for the secondary winding passes through the fourth oxide layer. Thus, the primary and second primary windings lie one above the other within the secondary winding.

Multiple primary windings may be provided in this way, and the two alternatives of the above two paragraphs may be combined to provide both horizontal and vertical stacking of primary windings.

In accordance with a second aspect of the invention, there is provided a method for manufacturing a transformer comprising primary and secondary windings, the method comprising, for each winding, providing first and second metal capping layers, and coupling the first and second metal capping layers together electrically in parallel by forming a metal connector passing through a substrate lying between the first and second metal capping layers.

Typically, for each winding, the metal connector is formed by making first and second trenches through the substrate and

depositing metal within the trenches to form a continuous layer from the top to the bottom surface of the substrate through the trench.

The first and second trenches may be made using an anisotropic etching process.

Alternatively, the first and second trenches may be made using a combination of an anisotropic etching process and grinding the substrate to reduce its thickness.

Typically, the metal is deposited within the trenches using a vapour deposition process or by electrolytic growth.

Normally, the metal capping layers are provided using a vapour deposition process or by electrolytic growth.

In one embodiment, the substrate is a silicon substrate and prior to depositing metal within the trenches and/or providing the metal capping layers, an oxidation step is performed followed by silicon nitride deposition to isolate the metal from the silicon substrate.

Physical vapour deposition of a titanium-copper alloy may be performed to enable the electrolytic growth of copper.

BRIEF DESCRIPTION OF THE DRAWINGS

Examples of the invention will now be described in detail with reference to the accompanying drawings, in which:

FIG. 1 shows a cross-sectional view through the windings of a transformer in a silicon die;

FIG. 2 shows a variation of the layout of the windings of the transformer of FIG. 1;

FIG. 3 shows a plan view of a transformer mounted in a package;

FIG. 4 shows a cross-sectional view through a concentric transformer in a silicon die;

FIGS. 5a to 5f shows the process steps for manufacturing a transformer in an oxide layer during a BiCMOS process;

FIG. 6 shows the process steps for manufacturing a concentric transformer in an oxide layer during a BiCMOS process; and

FIGS. 7a to 7c show graphically the improvement in electromagnetic coupling, quality factor and insertion loss provided by the transformer of FIG. 1.

DETAILED DESCRIPTION

A cross-sectional view of a transformer manufactured as an integrated circuit on a silicon die 1 is shown in FIG. 1. The transformer comprises a primary winding 2 and a secondary winding 3, both of which are embedded in the silicon die 1.

The primary winding 2 comprises two metal connectors 4, 5 passing through trenches 6, 7 formed in the silicon die 1. Metal capping layers 8, 9 lie on top of silicon die 1 in contact with the two metal connectors 4, 5, which therefore connect the metal capping layers 8, 9 together electrically in parallel.

Similarly, the secondary winding 3 comprises two metal connectors 10, 11 passing through trenches 12, 13 formed in the silicon die 1. Metal capping layers 14, 15 lie on top of silicon die 1 in contact with the two metal connectors 10, 11, which therefore connect the metal capping layers 14, 15 together electrically in parallel.

The metal connectors 4, 5, 10, 11 all fill their respective trenches 6, 7, 12, 13.

This configuration of the windings exhibits a low parasitic capacitive coupling between the primary and secondary windings due to the relatively large distance between the two windings. However, the electromagnetic coupling coefficient, k , is somewhat low for the same reason. Due to the relatively low capacitive coupling, this configuration is well suited to high frequency applications.

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A second configuration of the layout of the windings is shown in FIG. 2. Parts that are the same or have the same function as in FIG. 1 have been given the same reference numbers. This improves the electromagnetic coupling coefficient, k , significantly. However, this improvement comes at the expense of increasing the parasitic capacitive coupling between the primary and secondary windings. Due to the relatively high capacitive coupling, this configuration is more suited to low frequency applications.

In this second configuration, instead of forming four trenches, only three are formed. Metal connector 5 of the primary winding 2 passes through trench 16 and metal connector 10 of the secondary winding 3 passes through trench 17. However, metal connectors 4 of the primary winding 2 and metal connector 11 of the secondary winding 3 share a common trench 18 through the silicon die 1. Each of the metal connectors 4 and 11 is deposited on a respective side wall of the common trench 18, and the metal connectors 4 and 11 are isolated from each other by the gap between them. Their relative proximity enhances the electromagnetic coupling coefficient, k , between the primary and secondary windings 2, 3.

In order to manufacture a transformer as shown in FIGS. 1 and 2 in a silicon die 1, the following steps are carried out:

1) The silicon is anisotropically etched using the Deep Reactive Ion Etching (DRIE) technique where it is desired to form the trenches 6, 7, 12, 13 or 16, 17, 18. The actual pattern made by these trenches will depend on the desired characteristics of the transformer (e.g. the turns ratio and desired inductances of the primary and secondary windings 2, 3) being made and the presence of any other components on the silicon die 1, which may represent a layout constraint.

2) The anisotropic etching does not continue through the whole thickness of the silicon die 1. Instead, to complete the formation of the trenches 6, 7, 12, 13 or 16, 17, 18, the substrate is ground (typically so that the thickness of the silicon die 1 is in the order of several tenths of a micron) to expose the bottom of the trenches 6, 7, 12, 13 or 16, 17, 18 buried in the silicon die 1. Anisotropic etching is not generally used in isolation because the width of the trenches formed is proportional to their depth. Thus, limiting the duration of the etching allows construction of finer trenches.

3) The silicon die 1 is then oxidised, followed by deposition of silicon nitride deposition where it is desired to deposit metal for the metal connectors and capping layers. This step is carried out in order to isolate the metal (typically copper) from the bulk silicon. Copper diffusion can occur in the silicon otherwise.

4) Physical Vapor Deposition of a titanium-copper alloy is then carried out in the regions where it is desired to deposit metal for the metal connectors and capping layers. This enables growth of a copper metal layer.

5) The copper metal layer is then grown electrolytically in the trenches 6, 7, 12, 13 or 16, 17, 18. Depending on the duration of this step, the trenches 6, 7, 12, 13 or 16, 17, 18 can be either partially filled (leaving only a layer of metal on the side walls as in FIG. 2) or fully filled (as in FIG. 1).

6) The top metal capping layers 8, 14 are then grown electrolytically followed by the bottom metal capping layers 9, 15. The wafer only requires rotating between formation of the top and bottom metal capping layers as they will follow the same pattern.

The trenches will not be formed continuously. Instead, they must be interrupted periodically to prevent the structure collapsing.

The formation of metallic trenches in the silicon die 1 in this way leads to an increase in the cross-sectional area of

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metal available to carry current in the transformer when compared to prior art techniques. Moreover, it has been found that etching trenches in this way provides a high etching rate due to the open structure of the trenches. This can be contrasted with the etching of through-silicon vias, which with a high aspect ratio have a very weak etching rate.

FIG. 3 shows a plan view of a transformer similar to that shown in cross-section in FIG. 1. In this the primary 2 and secondary 3 windings can be seen, one within the other. The primary winding 2 terminates at through-silicon vias 20, 21 and the secondary winding 3 terminates at through-silicon vias 22, 23. As can be seen, the trenches in which the primary and secondary windings 2, 3 are formed are interrupted (to prevent collapse as mentioned above) at points 24.

Such a transformer can be packaged and sold as a separate component to be added in a multi-chip module (MCM). The signals are routed through the silicon using through-silicon vias 20, 21, 22 and 23, from which they can be connected to a PCB with solder bumps.

The through-silicon vias and the trenches can be made with the same process flow so the transformer can be manufactured and connected to the PCB without increasing the cost.

A variation on the transformers shown in FIGS. 1 and 2 is the concentric transformer shown in FIG. 4. Here the primary winding is formed inside the secondary winding.

The primary winding is formed in a middle silicon die 30, in which metal connectors 31 and 32 pass through trenches in middle silicon die 30 to electrically couple together metal capping layers 33 and 34.

The secondary winding has a top metal capping layer 35 on the top surface of an upper silicon die 36 and a bottom metal capping layer 37 on the bottom surface of a lower silicon die 38. These are joined by a pair of metal connectors running through all three silicon dice 30, 36, 38. The first metal connector thus runs through a trench 39a in upper silicon die 36, a trench 39b in middle silicon die 30 and a trench 39c in lower silicon die 38. Similarly, the second metal connector runs through a trench 40a in upper silicon die 36, a trench 40b in middle silicon die 30 and a trench 40c in lower silicon die 38.

The silicon dice 30, 36, 38 are separated by plastic spacers 41, 42. Electrical continuity of the metal connectors is ensured by interconnects, known as bumps, 43a, b and 44a, b.

This transformer can be manufactured using the same process as described above to form the pattern of trenches, metal capping layer and metal connectors shown in FIG. 4.

FIGS. 4a and 4b show two variants on the transformer of FIG. 4, which may be used to achieve different turns ratios. In each case, an additional primary winding (in parallel with the original primary winding) is formed within the secondary winding.

In FIG. 4a, two primary windings are stacked horizontally next to each other. The first primary winding is formed as explained above with reference to FIG. 4 and as denoted by the metal connectors 31, 32 and metal capping layers 33, 34. The second primary winding 110 is formed in the same way by making trenches in middle silicon die 30 (at the same time as trenches for the metal connectors 31, 32) and filling them with metal and providing metal capping layers, again in the same way and at the same time as metal capping layers 33, 34. The second primary winding 110 has the same structure as the first primary winding although the individual metal capping layers and metal connectors are not separately denoted.

In the variant of FIG. 4b, two primary windings are stacked vertically, one above the other. The first primary winding is formed as explained above with reference to FIG. 4 and as denoted by the metal connectors 31, 32 and metal capping

layers **33**, **34**. The second primary winding **112** is formed in the same way, but in this case it is formed in a further silicon die **111**, which is processed in the same way as silicon die **30**. Thus, the second primary winding **112** is formed in the same way as the first by making trenches in the further silicon die **111** and filling them with metal and providing metal capping layers. The second primary winding **112** has the same structure as the first primary winding although the individual metal capping layers and metal connectors are not separately denoted. The further silicon die **111** lies above the plastic separator **41** and is separated from the top silicon die **36** by another plastic separator **113**. Again, bump interconnects **43c**, **44c** are provided in the plastic separator **113** along with metal connectors **39c**, **40c** in silicon die **111** to connect the metal capping layers **35**, **37** together.

Providing two primary windings within the secondary winding in this way gives a turns ratio of 2:1 (primary:secondary). Different turns ratios may be provided by forming a different number of primary windings (for example, 3 or more) within the secondary. A combination of vertically and horizontally stacked primaries may be used, for example to achieve 4 primary windings with two windings on the silicon die **30** and two on the further silicon die **111**.

Of these two variants, the structure shown in FIG. **4a** is best suited to use with silicon substrates (i.e. the type of processing shown and described with reference to FIG. **1**) because the horizontal distance between the windings can be kept smaller than the thickness of a bump interconnect. Thus, the electromagnetic coupling coefficient is optimised with the FIG. **4a** variant.

FIGS. **5a** to **5f** shows another way of making a transformer according to the invention, this time using a BiCMOS process such as the QuBIC process. In this case, the deep trenches between metallisation layers can be realised in the dielectric layers using the Deep Trench Isolation (DTI) principle.

In FIG. **5a**, copper is deposited and then etched on a silicon die **50** to obtain the bottom metal capping layers **51**, **52**, **53**, **54** for each of the primary and secondary windings.

An oxide layer **55** is then deposited above the silicon die **50** and the bottom metal capping layers **51**, **52**, **53**, **54** in FIG. **5b**. Chemical mechanical polishing (CMP) of the oxide layer **55** is then carried out for planarisation.

In FIG. **5c**, a photoresist layer **56** is deposited to leave the pattern of the trenches required exposed for etching.

Anisotropic etching is then performed to form the trenches **57a** to **57h** and the photoresist layer **56** is subsequently removed. The trenches **57a** to **57h** can be seen in FIG. **5d**.

Copper metal is then used to fill the trenches **57a** to **57h**, which is achieved by chemical vapour deposition (CVD). This forms the metal connectors **58a** to **58h**, as seen in FIG. **5e**. This is followed by a chemical mechanical polishing step for planarisation of the oxide layer **55** with metal connectors **58a** to **58h** embedded within.

Copper is then deposited above the oxide layer **55** to form the top metal capping layers **59**, **60**, **61**, **62** in FIG. **5f**, which shows the finished transformer. As can be seen, the primary and secondary windings are formed in a similar layout to the embodiment of FIG. **1**.

A similar process can be used to form a transformer like that of FIG. **4**. This process is shown in FIGS. **6a** to **6m**. Firstly, in FIG. **6a** copper is deposited and then etched on a silicon die **70** to obtain the bottom metal capping layers **71a**, **71b** for the outer secondary winding.

An oxide layer **72** is then deposited above the silicon die **70** and the bottom metal capping layers **71a**, **71b** of the second-

ary winding in FIG. **6b**. Chemical mechanical polishing (CMP) of the oxide layer **72** is then carried out for planarisation.

Copper is deposited and then etched on the oxide layer **72** to obtain the bottom metal capping layers **73a**, **73b** for the primary winding. This is shown in FIG. **6c**.

A second oxide layer **74** is then deposited above the oxide layer **72** and the bottom metal capping layers **73a**, **73b** of the primary winding in FIG. **6d**. Chemical mechanical polishing (CMP) of the oxide layer **74** is then carried out for planarisation.

In FIG. **6e**, a photoresist layer **75** is deposited to leave the pattern of the trenches required for the metal connectors of the inner, primary winding exposed for etching.

Anisotropic etching is then performed to form the trenches **76a** to **76d** and the photoresist layer **75** is subsequently removed. The trenches **76a** to **76d** can be seen in FIG. **6f**.

Copper metal is then used to fill the trenches **76a** to **76d**, which is achieved by chemical vapour deposition (CVD). This forms the metal connectors **77a** to **77d** for the primary winding, as seen in FIG. **6g**. This is followed by a chemical mechanical polishing step for planarisation of the oxide layer **74** with metal connectors **77a** to **77d** embedded within.

Copper is then deposited above the oxide layer **74** to form the top metal capping layers **78a**, **78b** for the primary winding in FIG. **6h**.

A third oxide layer **79** is then deposited above the oxide layer **74** and the top metal capping layers **78a**, **78b** of the primary winding in FIG. **6i**. Chemical mechanical polishing (CMP) of the oxide layer **79** is then carried out for planarisation.

In FIG. **6j**, a photoresist layer **80** is deposited to leave the pattern of the trenches required for the metal connectors of the outer, secondary winding exposed for etching.

Anisotropic etching is then performed to form the trenches **81a** to **81d** and the photoresist layer **80** is subsequently removed. The trenches **81a** to **81d** can be seen in FIG. **6k**.

Copper metal is then used to fill the trenches **81a** to **81d**, which is achieved by chemical vapour deposition (CVD). This forms the metal connectors **82a** to **82d** for the secondary winding, as seen in FIG. **6l**. This is followed by a chemical mechanical polishing step for planarisation of the oxide layer **79** with metal connectors **82a** to **82d** embedded within.

Copper is then deposited above the oxide layer **79** to form the top metal capping layers **83a**, **83b** in FIG. **6m**. The resulting transformer, like that of FIG. **4**, has a primary winding surrounded by the secondary winding.

Multiple primary windings may be provided within the secondary winding as in the transformers shown with reference to FIG. **4**. In this case, where the trenches and deposition of metal are performed on oxide layers rather than on silicon, the FIG. **4b** variant is most advantageous. This is because the bump interconnects are not required as the oxide layers can be formed contiguously without the need for plastic separators. Thus, if the oxide layer between windings is kept small enough the electromagnetic coupling coefficient can be made correspondingly high.

FIGS. **7a** to **7c** show the results of simulation carried out on a transformer with the same architecture as that of FIG. **1**. The simulation results are presented as the difference between the absolute results for the architecture of FIG. **1** and the Shibata architecture, mentioned above.

In FIG. **7a**, the difference in the electromagnetic coupling co-efficient, k , expressed as the percentage difference between the architecture of FIG. **1** and the Shibata architecture (i.e. the ratio of the difference in value between the two co-efficients to the coefficient for the Shibata architecture

multiplied by 100%) versus frequency is shown. As can be seen, there is a significant improvement with the architecture of FIG. 1.

FIG. 7b shows the difference in the quality factor for the primary winding, expressed as the percentage difference between the architecture of FIG. 1 and the Shibata architecture versus frequency. Again, there is a significant improvement with the architecture of FIG. 1.

FIG. 7c shows two plots of results. Plot 100 relates to the difference in insertion loss between the architecture of FIG. 1 and the Shibata architecture versus frequency. The values for the insertion loss are provided, as the percentage difference between the architecture of FIG. 1 and the Shibata architecture, by the y-axis on the left hand side of the graph. There is a marked decrease in insertion loss, especially around 10 GHz.

The second plot 101 relates to the difference in the transmission parameter S12 between the architecture of FIG. 1 and the Shibata architecture versus frequency. The values for S12 are provided, as the percentage difference between the architecture of FIG. 1 and the Shibata architecture, by the y-axis on the right hand side of the graph. There is a marked increase in S12, especially around 10 GHz.

It will be appreciated that although copper has been used as the metal to form the components of the transformers throughout, other metals such as aluminium or gold (or indeed, any other metal that is compatible with existing semiconductor fabrication processes) could be used. Similarly, different semiconductor materials than silicon could be used. For example, processes based on germanium, gallium arsenide, or silicon-germanium semiconductors could be used.

Other variations to the disclosed embodiments can be understood and effected by those skilled in the art in practicing the claimed invention, from a study of the drawings, the disclosure, and the appended claims. In the claims, the word “comprising” does not exclude other elements or steps, and the indefinite article “a” or “an” does not exclude a plurality. A single processor or other unit may fulfill the functions of several items recited in the claims. The mere fact that certain measures are recited in mutually different dependent claims does not indicate that a combination of these measures cannot be used to advantage. Any reference signs in the claims should not be construed as limiting the scope.

The invention claimed is:

1. A transformer comprising primary and secondary windings, each winding having first and second metal capping layers coupled together electrically in parallel by a metal connector passing through trenches formed in a substrate lying between the first and second capping layers, wherein the transformer comprises two primary windings that are stacked vertically, wherein the secondary winding surrounds the two primary windings, wherein the two primary windings are formed in first and second dice, wherein the secondary wind-

ing is formed in a third silicon die and in a fourth die that are separated by the first and second dice, and wherein the first, second, third and fourth dice are separated by plastic separators.

2. A transformer according to claim 1, wherein the substrate is a silicon substrate and each of the first and second metal capping layers lies on top and bottom surfaces of the silicon substrate respectively.

3. A transformer according to claim 2, wherein the substrate is an oxide layer and each of the first and second metal capping layers lies on top and bottom surfaces of the oxide layer respectively.

4. A transformer according to claim 1, wherein, for each winding, the substrate comprises first and second trenches, and the metal connector comprises first and second parts passing through the first and second trenches respectively, each of the first and second parts coupling the first and second metal capping layers together electrically in parallel.

5. A transformer according to claim 1, wherein, for each winding, the substrate comprises a first trench, a first part of the metal connector passing through the first trench, the substrate further comprising a common trench through which second parts of the metal connectors for each winding pass electrically isolated from each other, each of the first and second parts coupling the first and second metal capping layers together electrically in parallel.

6. A transformer according to claim 1, wherein the substrate is a first silicon substrate lying between second and third silicon substrates, each of the first and second metal capping layers for the primary winding lying on top and bottom surfaces of the first silicon substrate respectively and each of the first and second metal capping layers for the secondary winding lying on top and bottom surfaces of the second and third silicon substrates respectively, the metal connector for the primary winding passing through the first silicon substrate and the metal connector for the secondary winding having first and second parts passing in parallel through the first, second and third silicon substrates such that the secondary winding surrounds the primary winding.

7. A transformer according to claim 1, wherein the substrate is a first oxide layer lying between second and third oxide layers, each of the first and second metal capping layers for the primary winding lying on top and bottom surfaces of the first oxide layer respectively and each of the first and second metal capping layers for the secondary winding lying on top and bottom surface of the second and third oxide layers respectively, the metal connector for the primary winding passing through the first oxide layer and the metal connector for the secondary winding having first and second parts passing in parallel through the first, second and third oxide layers such that the secondary winding surrounds the primary winding.

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